

PULSED ULTRAVIOLET FLUORESCENCE FOR IN-PROCESS SURFACE CONTAMINATION DETECTION*

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ABSTRACT

As part of the NASA Bondline Solid Propulsion Integrity Program (SPIP), a technique to detect and quantify surface contamination on SRM bonding surfaces was developed. This technique is based upon imaging low levels of UV excited fluorescence from the contamination. We have been investigating two enhancements of the technique. First, a pulsed source of broadband UV excitation light synchronized to the gated intensifier of the low-light-level video camera was incorporated. As compared to a c.w. system, this enhancement reduces interference from ambient room lighting. The second enhancement involved the addition of a motorized filter wheel to allow for computerized selection of the optical filters. Using multispectral techniques, the image signal-to-noise may be optimized with respect to a particular contaminant and substrate combination. A bench-top pulsed, multispectral UV Fluorescence (UVF) imaging system was constructed. Several different SRM material samples including aluminum alloys, steel alloys, carbon phenolic composite, coated metals, liner, and NBR insulation were inspected with excellent results. Subsequently, a portable UVF system was constructed based on similar technology. The portable system was used to inspect the entire inner surface of a BATES test case in a factory setting.

INTRODUCTION

Case-to-insulation and insulation-to-propellant bondline flaws are considered to be a major cause of Solid Rocket Motor (SRM) failures¹. Weak bonds and delaminations are often the result of contamination of surfaces during production. As part of NASA's SPIP Bondline program, we have been investigating the application of Ultraviolet Fluorescence Imaging (UVFI) to surface contamination detection and quantification. This technique shows promise as a rapid, economical in-process inspection method. The goal of this on-going work is to develop a rapid, non-contact, robust, and economical method for the in-process detection and quantification of contamination on SRM bonding surfaces.

Initial work included the development of an experimental lab breadboard system to investigate feasibility². Lab experiments with computerized image analysis demonstrated detection of preservative oil on a grit blasted steel surface down to about 1 microgram per square centimeter (~1 milligram per square foot). A prototype inspection system was subsequently designed and fabricated³. This system utilized c.w. illumination and was used to inspect the Bondline Analog Motor #1 case components during the manufacturing process. Development of the UVFI technique continued with the construction of a transportable bench-top system for the inspection of medium size samples and other developmental work^{4,5}. This system was used to inspect the Bondline Contamination Sensitivity samples at Thiokol Space Division and was demonstrated to a joint meeting of the SPIP Bondline and MSFC Surface Contamination Team.

This paper covers subsequent UVFI development activities. We implemented two enhancements that we had proposed initially: (1) pulsed illumination with gated intensification and (2) multispectral imaging. Pulsed illumination with gated intensification reduces interference from room light. Multispectral imaging allows for the immediate selection of filters to enhance the system signal-to-noise with respect to substrate and contaminant. A bench-top prototype system was constructed and used to demonstrate the successful detection and quantification of HD-2 grease on grit-blasted metals, coated metals, graphite-epoxy composite, and the RSRM liner and insulation⁶. We believe that this was an important achievement since the coated metals, composite, liner, and insulation all exhibit an inherent fluorescence of their own. The elastomeric RSRM liner and insulation surfaces were of particular interest since they are critical bonding surfaces which can not be cleaned easily, and for which OSEE does not work. The pulsed, multispectral UVFI system was transported to Huntsville, Alabama for some of the tests, and to the NASA Langley Research Center for demonstration to a meeting of the NASA Senior Management Council.

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A portable UVF system was constructed based on the technology demonstrated in the bench-top unit. The compact sensor head of the new system could be mounted on manipulation systems for the inspection of SRM case components. Using the portable system, the inner grit-blasted surface of a BATES (Ballistic Test and Evaluation System) case was inspected for contamination in a factory setting. A mosaic image yielding a calibrated mapping of the surface contamination was generated.

THEORY OF OPERATION

UV FLUORESCENCE FOR SURFACE CONTAMINATION DETECTION

In the UVFI technique, the surface to be inspected is illuminated with filtered ultraviolet light. The filters transmit a selected band of ultraviolet light while blocking other wavelengths. After absorbing an ultraviolet photon, the contaminant can re-emit some of the energy as another photon of lower energy through the process of fluorescence. Since the fluorescent photons have a different energy than the illumination, and hence their wavelengths are shifted, they may be detected separately. UVFI quantifies the level of contamination by measuring the amount of fluorescent light emitted by the material for a known UV irradiation. The level of contamination detectable depends upon the intensity of the excitation light, the absorption and emission efficiencies of the fluorescent material, the sensitivity of the imaging system, and the efficacy of rejection of ambient light.

The fraction of monochromatic light transmitted through an absorbing medium follows an exponential relationship:

$$\frac{I}{I_0} = e^{-\mu(\lambda_i)\rho l} \quad (1)$$

where $\mu(\lambda_i)$ is the mass absorption coefficient (a function of the excitation wavelength), ρ is the material density, and l is the path length. The relative amount absorbed is one minus the amount transmitted. If we assume that the material is optically thin, then the small argument approximation to the exponential can be used to give the simple relationship:

$$A \approx \mu(\lambda_i)\rho l \quad (2)$$

where A is the fraction of incident light absorbed. If we also assume normal incidence, and no self absorption of the emitted light in the layer, the above relationship can be used in an estimation of the relative amount of fluorescent energy emitted. Since reflection of the incident ultraviolet light increases the path length, and reflection of some of the emitted photons back toward the detector could increase the number of photons detected, the differential energy flux emitted into the half-sphere toward the detector may be approximated with the following equation:

$$E_F(\lambda_F) \approx \frac{1}{2} \int_{\lambda_0}^{\lambda_F} E_i(\lambda_i) [1 + R_i(\lambda_i)] [1 + R_F(\lambda_F)] \varepsilon(\lambda_i, \lambda_F) \mu(\lambda_i) \rho l d\lambda_i \quad (3)$$

where: E_i = incident ultraviolet energy flux
 $E(\lambda_F)$ = emitted fluorescent energy flux
 $R_i(\lambda_i)$ = surface reflectivity for ultraviolet light
 $R_F(\lambda_F)$ = surface reflectivity for emitted light
 $\varepsilon(\lambda_i, \lambda_F)$ = relative fluorescence efficiency at wavelength λ_F for excitation at λ_i .

The amount of a particular material per unit area can be inferred from the intensity of the fluorescence, with reference to a calibration curve generated for that material at a particular fluorescent wavelength and source excitation parameters. A procedure for generating such calibration curves was developed in our previous work¹. In general, a calibration curve generated for one possible contaminant can not be used to accurately infer the level of contamination from another source.

The fluorescent light emitted by the contaminant is imaged with a low-light video camera. An optical filter passes selected band widths of the fluorescent light while blocking interfering light from the UV source. The use of an area imager allows relatively rapid inspection of large surface areas as compared to a point spectrographic technique, for example. Figure 1 shows a simplified schematic of the system concept.

MULTISPECTRAL OPERATION

Different contaminants exhibit different absorption and fluorescent emission spectra. In order to optimize the signal from a particular contaminant, while minimizing interference from ambient light sources, we have incorporated computer controlled filter wheels in our UVFI systems. A filtered pass-band can be selected to give the best signal-to-noise for a particular application. Figure 2 shows the concept of selectable filter pass-bands at longer wavelengths than the excitation light. For non-metallic substrates, multispectral imaging can be used to compare images taken at different wavelengths to improve discrimination between a contaminant and a fluorescing substrate.

PULSED OPERATION

Operation under normal room lighting conditions is a desirable feature of an UVFI contamination detection system. By utilizing a pulsed UV excitation source and gating the image intensifier, operation under ambient room lighting can be achieved. This is accomplished by gating the intensifier in synchronism with short pulses of light from the UV source, yielding a short duty cycle in which the imager is sensitive to room light interference. For example, if the intensifier is gated on 60 times per second (video-field rate) for 5 μ s each time, then the "on" duty cycle is only 3×10^{-4} . The interfering signal from room light would then be reduced by this factor over a c.w. system. Other advantages of a pulsed source of UV is an instant on/off capability, reduced UV exposure to the substrate and a reduction in heat generation.

Xenon flashlamps are attractive as sources of pulsed UV. Flashlamps may be pulsed at the repetition rate needed with pulse energies exceeding a Joule. Light production efficiency can peak at about 10% for short-arc bulb flashlamps and at 40% for linear ones. Flashlamps designed and operated for UV emission can produce broadband UV in the 200 to 400 nm region that accounts for 34% of total light output⁷. As compared to the UV line emissions from lasers or certain other arc lamps (e.g. mercury arc lamp), the broadband nature of the Xenon flashlamp spectrum is advantageous for exciting fluorescence from unknown contaminants where the details of the absorption spectrum can not be anticipated, or for multispectral excitation where the excitation pass-band is selected with filters. Additionally, Flashlamp systems are simpler to operate, more durable, and lower cost than UV lasers.

UVF SYSTEM DESCRIPTIONS

PULSED MULTISPECTRAL BENCH-TOP PROTOTYPE

As part of the NASA SPIP Bondline Program, SAIC constructed a prototype pulsed UVFI system. This bench top system could inspect medium sized specimens, such as 8" x 12" witness panels, and be transported for off-site experiments. The optical instrumentation was housed in a black acrylic enclosure and cooled with filtered air. The imaging components were mounted on top of a larger sample enclosure, also constructed from black acrylic. The sample enclosure protected the experiment from airborne contamination, reduced light interference when operating in c.w. mode, and protected the operator from UV exposure when required. A block diagram of the system is shown as Figure 3. Figure 4 is an annotated photograph of the imaging components with the cover removed.

A Xenon flashlamp was utilized as the source of UV irradiation. The flashlamp subsystem includes a triggerable charging supply and a short-arc bulb fitted with a sapphire window for UV transmission. Electrical capacitance and excitation voltage were selected to produce 0.7 Joule pulses. At a video field rate of 60 Hz, this yields about 40 watts average power to the lamp. The lamp was only pulsed when images were actually being acquired. Each individual pulse was about 8 microseconds in duration. The UV light was condensed, filtered, and projected onto the sample. The filter had a center wavelength (CWL) of 350 nm.

A gated, GEN II intensified CCD camera imaged the low level fluorescence from the contaminant. A motorized filter wheel selected the pass-band of light to be transmitted to the video camera. By using a delay pulse generator, the lamp was flashed in synchronization with the video field during the vertical retrace period. The camera intensifier gate was turned on only during the lamp pulse duration to help reject interference from ambient light. The video images were acquired, processed, and stored digitally with a Matrox MVP-AT image processor. Housed in a personal computer, the image processor provided for integration of the images to reduce statistical noise, normalization of the imager response,

and quantitative image analysis tools. SAIC-developed software controlled the image processor, filter wheel position, and flashlamp operation. The resulting images were displayed on a color monitor. Hardcopies of the images could be generated when required on a color video printer.

PORTABLE UVF SYSTEM

We constructed a portable UVF imaging system based on the technology demonstrated with the bench-top system. This system utilizes two adjustable linear xenon flashlamps as the excitation sources. Both lamps are filtered with special glass which passes a broad-band UV spectrum peaked at 340 nm, while blocking the visible and short wave UV portions of the spectrum. Each lamp is pulsed with 1.0 Joule of energy at 60 Hz, synchronized with the video field rate.

The intensified CCD camera, path bending optics, and motorized filter wheels are housed in a 18 x 11 x 7 inch aluminum enclosure. The flashlamp brackets are mounted on the outside of the enclosure. A photograph of the portable UVF system sensor enclosure is shown as Figure 5. Figure 3, described above, is a block-diagram of the system. As with the bench-top system, the video images were acquired and stored digitally with a Matrox MVP-AT image processor. The system was controlled with a personal computer.

EXPERIMENTAL PROCEDURES: EVALUATION OF BENCH-TOP SYSTEM

IMAGE PROCESSING AND ANALYSIS PROCEDURE

Image processing procedures and software were developed to semiautomatically analyze the UVF images. During acquisition, the images were integrated in order to reduce the noise from statistical or electronic sources. For the measurements discussed here, 256 video frames were averaged together. This should reduce noise from statistically random sources by a factor of 16. After acquisition, the raw images were stored as digital files. The next step was to subtract an offset image from the data. The offset image, acquired beforehand, represents the imager dark current. The image data was then multiplicatively corrected for variations in imager gain, lamp illumination, and lens fall-off across the field of view. The reference image utilized in this step was obtained beforehand by imaging a uniformly fluorescent screen as a standard. The resulting 8 bit corrected images were analyzed to obtain intensity information. A predetermined region on the sample was defined with a software cursor. Average pixel intensity and standard deviation was recorded for the region outlined by the cursor, and a histogram of the pixel intensities displayed on the monitor. When desired, a hardcopy could be generated with the video printer.

DEMONSTRATION ON ASRM MATERIALS

The samples inspected during this portion of the work were supplied by Aerojet/ASRM. Each sample was 12" x 2" with various thicknesses up to 0.5". The sample materials were HP 9-4-30 and D6AC steel, 6061 T6 and 7075 aluminum, Cermatel 64-1 and 1207/1208 coated metal samples, and carbon phenolic composite. The bare steel and aluminum samples were initially grit-blasted, vapor degreased with 1,1,1 trichloroethane (TCA), and NVR tested. The other samples were wiped with TCA, pressure flushed with TCA, flushed with P-Freon, and NVR tested. The NVR testing was performed in the MSFC NDE laboratory.

Conoco HD-2 grease was used as the test contaminant. Controlled surface concentrations were applied by spraying a solution of HD-2 in TCA onto the samples and allowing the solvent to evaporate. Clean, weighed aluminum foil sheets were placed at each end of the samples. The contaminant solution was applied with an airbrush passed along the length of the samples and foil pieces. One end of the samples was masked with foil to provide a clean control area. An estimate of the surface concentration of contaminant remaining was obtained by comparing the weight of the foil pieces after solvent evaporation. The average of the values for each end was used as the estimate of the level of contaminant on the sample. The samples were cleaned and contamination applied at the MSFC NDE Lab facilities. They were then placed in clean plastic bags filled with dry nitrogen for transportation. The UVFI inspection was performed at the SAIC/Huntsville facility. Transportation from one location to the other required about 15 minutes.

After an initial cleaning, the samples were inspected with the bench-top prototype UVF system. A nominal level of 10 mg/ft² of HD-2 was then applied to the samples. UVFI measurements were made at that level followed by a recleaning of the samples. Subsequently, nominal levels of 10, 30, 60, and 90 mg/ft² were applied to the sample top surface and inspected with the UVFI system. The levels above 10 mg/ft² were obtained by adding additional material onto the previous layers. Fresh foil pieces were used at each step.

RSRM LINER AND NBR INSULATION

The UVFI system was used to ascertain the detectability of HD-2 grease on RSRM liner and cured asbestos NBR insulation. The liner and insulation samples were supplied by Thiokol. The grease was applied to the liner sample using the following procedure in the SAIC San Diego laboratory. Solutions of HD-2 grease in TCA were prepared in concentrations of 1.00g/l, 2.00g/l, and 5.00g/l. The liner sample was centered on a plexiglass base of known area (205 cm²), which was then carefully covered with 0.7 mil aluminum foil. Rectangular windows of area 30 cm² were then cut from the foil covering the liner sample. The foil was carefully removed, weighed, and replaced over the liner sample. A Paasche model H airbrush was then used to uniformly spray the covered sample. The sample was divided into four sections of equal area, each centered on a window in the foil. To produce different concentrations of contaminant in each window, the separate sections were masked off by placing a cardboard sheet perpendicular to the sample surface, with the cardboard edge along the dividing line between sections of the sample. Using this technique, concentrations in the ratio 1:2:3:4 were typically applied to the four sections without significantly contacting the surface with the mask. The solvent was allowed to evaporate between applications, and after the completion of spraying. The foil was then carefully removed and weighed. The resulting liner sample contained four rectangular areas of surface contaminant with concentrations in the nominal ratio 1:2:3:4, with absolute levels dependent upon the concentration of the solution and spraying speed and measured by subtracting the weight of the foil before and after spraying. Spraying was done manually with a timer, and repeated trials indicated that the error in local contaminant concentration (determined by foil weighing) using this method was about +/-15%.

The application of the grease to the insulation was more problematic since the insulation tended to absorb the HD-2 grease solution. To reduce uptake of the grease and TCA by the insulation, a more concentrated solution was used, and the airbrush parameters were adjusted so that the TCA was mostly evaporated before the sprayed solution hit the insulation surface. In this way, a uniform layer of HD-2 grease could be applied without significant penetration into the insulation. Subsequently, we installed a mechanized translation stage for spraying the sample. This improved the uniformity and reproducibility of the application of contaminants. The UVF inspection and analysis were performed as described in the preceding subsections.

RESULTS: BENCH-TOP SYSTEM

RESULTS ON GRIT BLASTED METALS AND OTHER ASRM MATERIAL SAMPLES

As an example, Figure 6 is a reproduction from a hardcopy of the analyzed UVF image for a grit blasted HP-9 steel sample. The image was taken with 350 nm CWL excitation and a 450 nm CWL, 66 nm FWHM fluorescence filter and is representative of typical results. The sample was contaminated with HD-2 grease at 9.4 mg/ft². An histogram of the intensity values for the delineated box is shown. An uncontaminated control region is shown on the left. As can be seen from this image, the presence of HD-2 grease at this level is easily detectable.

Figures 7 and 8 are examples of plots of measured intensities as a function of the fluorescence filter center wavelength. The plots are for grit blasted 6061 T6 aluminum and carbon phenolic composite respectively. The figures show a plot for the as-cleaned material and one for the material contaminated with about 10 mg/ft² of HD-2. Each filter has a bandwidth of approximately 25 to 30 nm. The points at 400 nm show that there is some overlap of the excitation spectrum with this particular filter pass-band, as expected. The intensity measured at this point gives a rough indication of the surface reflectivity for the clean materials at this wavelength, with the aluminum being the highest. The clean aluminum, steel alloys, and 64-1 coating show very little signal for 450, 500, 550, and 600 nm. The carbon phenolic composite and 1207/1208 coating show a significant measured intensity in this range which represents fluorescence from the clean substrate. The HD-2 fluorescence peaks in the 450 to 500 nm range. The intensity associated with the HD-2 fluorescence is not only a function of the surface concentration, but of the substrate reflectivities for the excitation and emission wavelengths as discussed above. We feel that this is why the signal from the HD-2 on the composite is relatively lower than that for the aluminum. The HD-2 solution is also apparently being partially absorbed by the composite at the time of application, which would be a contributing factor in reducing the signal level from the contaminant. Even with these factors, the effect from the HD-2 is easily observable for all of the samples tested.

An emission CWL of 450 was chosen for further comparisons since the fluorescence of the grease is high there with the inherent fluorescence from the samples being relatively low. Three HP-9 steel samples were tested independently and the measured intensity versus nominal HD-2 level plotted together in Figure 9. The data from all three samples fall along the same linear fit fairly well. Figures 10 through 12 show plots of intensity versus HD-2 level for 6061 aluminum, 1207/1208 coating, and carbon phenolic respectively. Two plots are shown for each graph, one for a filter with a 28 nm FWHM pass-band, and another for a 66 nm FWHM. Straight line fits are shown for both plots. Deviations

from the linear fit are apparently mostly due to systematic errors in the amount of contaminant applied rather than random errors in the measurement. The zero offset with the 66 nm FWHM filter for the 1207/1208 and composite samples is due to the inherent fluorescence of the substrates. The narrower filter reduces this effect.

RESULTS FROM RSRM LINER AND CURED NBR INSULATION

Contaminated liner samples were examined using three different excitation spectra and six different camera filters. Some results for HD-2 grease on UF2197 liner are shown in Figure 13. A horizontal profile of the intensity across the sample for 2.12 second integration time, averaged over the vertical extent of the contaminant windows, is plotted. For this data, the UV lamp output was filtered at 254 nm with a 44 nm FWHM, and the camera input was filtered at 450 nm with a 66 nm FWHM. The top row shows regions of HD-2 grease at concentration levels of 84, 63, 42, and 21 micrograms/cm² +/-15%.

Preliminary results indicate that HD-2 grease concentrations of less than 15 micrograms/cm² may be easily detected on clean cured NBR insulation. Additional work is on-going to determine the sensitivity to contamination on non-asbestos insulation with the new portable UVF system.

INSPECTION OF BATES CASE WITH PORTABLE UVF SYSTEM

We were invited by Thiokol to use our portable UVF system to inspect a BATES case to verify surface cleanliness. The case was 70" long with a 28" ID. It was fabricated from A515 steel with the inner surface grit-blasted except for 5.3" at each end. The case was previously degreased with TCA. A possible contaminant was Mil-C-16173D corrosion preventative oil.

The portable UVF system was shipped to Thiokol Corporation Strategic Operations for the inspection. The BATES case had been previously mounted on Thiokol's manipulator. The manipulator provided for rotation of the case under computer control. A motorized linear translation stage ran along the inside of the case. The UVF system was mounted to the translation stage, which allowed positioning of the imager longitudinally. The UVF head was oriented so that the 12" x 12" imaged field of view (FOV) was along the horizontal centerline. Figure 14 is a diagram of the inspection set-up showing the rotation direction and starting positions. The motion of the UVF sensor head and rotation of the sample was controlled by a Thiokol operator at the motor control console. We imaged the inner surface of the case by initially translating the sensor head to 9 positions along the case longitudinally, providing 9 overlapping images. The case was then rotated approximately 33 degrees, and a new series of images along the length taken. The rotation provided 11 overlapping views along the circumference. Ninety-nine images provided 100% coverage of the inner surface with this procedure.

Images were integrated for 128 video frames (4.3 seconds) to reduce statistical noise. After each image acquisition, the data was stored digitally and the sensor/case moved to the next position. The first image of each longitudinal series included calibration coupons in the FOV which were mounted on the manipulator frame at the end of the case. One coupon was clean. The other had 11 mg/ft² of Mil-C-16173D oil applied to it. Both coupons were grit-blasted D6AC steel, and were 2" x 2" in size. The coupons provided a calibration for each longitudinal run to verify system stability. After return to the SAIC facilities in San Diego, the images were processed to obtain a mapping of the inner surface of the case and verify system performance. The first step involved subtracting a "dark current" image, followed by gain normalization. The 99 images were then "cut and pasted" together in an image processor to generate a mosaic image of the entire inner surface of the case and calibration coupons. Examples of results are to be presented at the Bondline Annual Technical Review to be held concurrently with this conference.

CONCLUSIONS

We have successfully demonstrated UVF imaging as a viable surface contamination inspection tool. This technique is applicable to metallic or composite cases, and liner and insulation. It can be used as an in-process inspection tool or as an aid in the certification of new cleaning procedures. Our technique benefits from two enhanced operating modes: pulsed operation to help reject interfering ambient light, and multispectral imaging to improve signal to noise on organic substrates. We have fabricated two systems based on this technology developed on the Bondline Program. The bench-top prototype was utilized to evaluate the applicability of the technology to a variety of samples with very good results. We continued our development with the fabrication of a portable UVF system. The new system was successfully demonstrated on a metallic BATES case in a factory setting. We plan to complete laboratory tests of the new system on insulation in the near future.

ACKNOWLEDGEMENTS

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We would like to thank David Williams of Aerojet for arranging the tests on ASRM materials, and Lydia Biegert of Thiokol for providing RSRM liner and insulation samples. We also thank Scott Rainwater of SAIC, Huntsville for his assistance in the preparation of the samples at MSFC. Jeffery Colborn of SAIC performed the tests on elastomeric materials. Finally, we thank George Berkeley of Thiokol for the invitation to perform the BATES case inspection and his help in making arrangements, and Jeff Buttler for his assistance during the on-site preparation and inspection.

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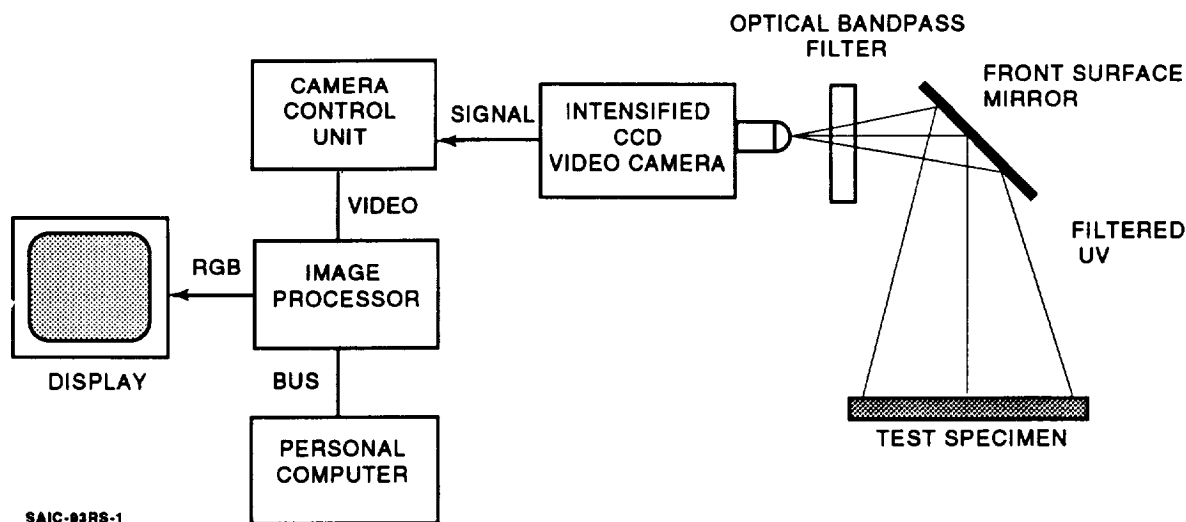


Figure 1. Simplified Diagram of UVFI System.

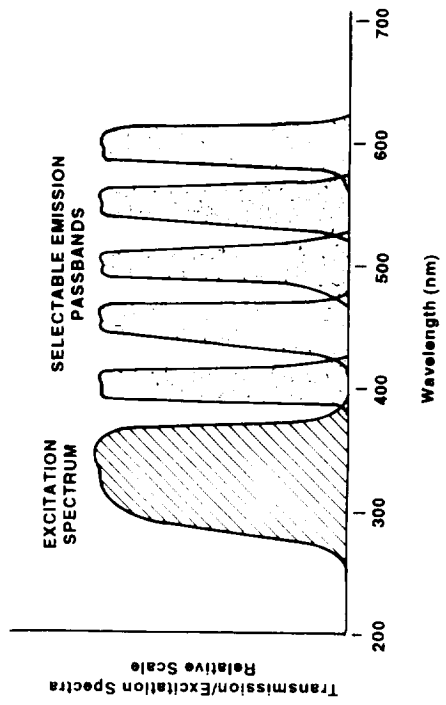


Figure 2. Multispectral Fluorescence Imaging Concept.

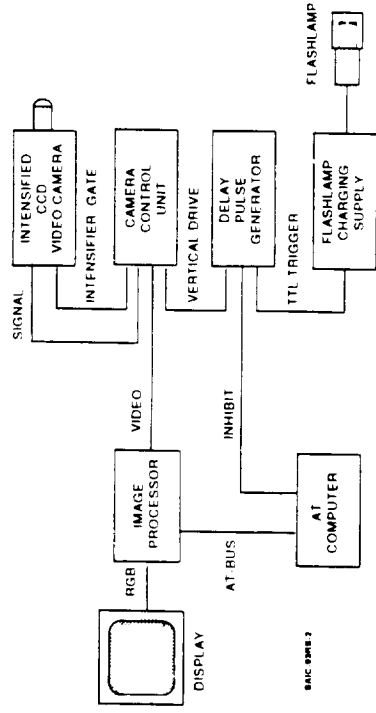


Figure 3. Pulsed UVF System Block Diagram.

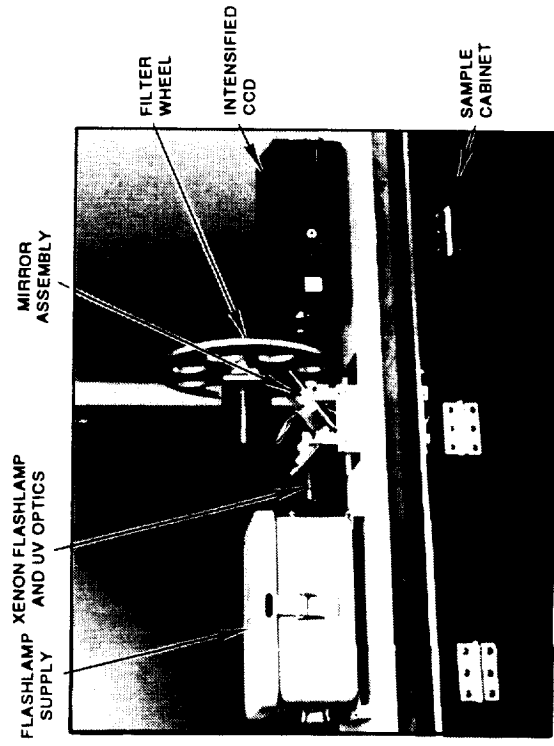


Figure 4. Photograph of Bench-Top Pulsed Multispectral UVFI System (Cover Removed).

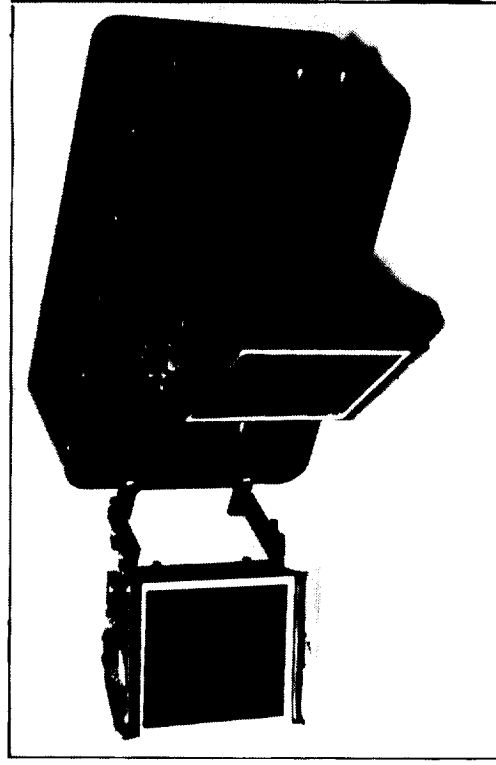


Figure 5. Portable, Pulsed, Multispectral Inspection.

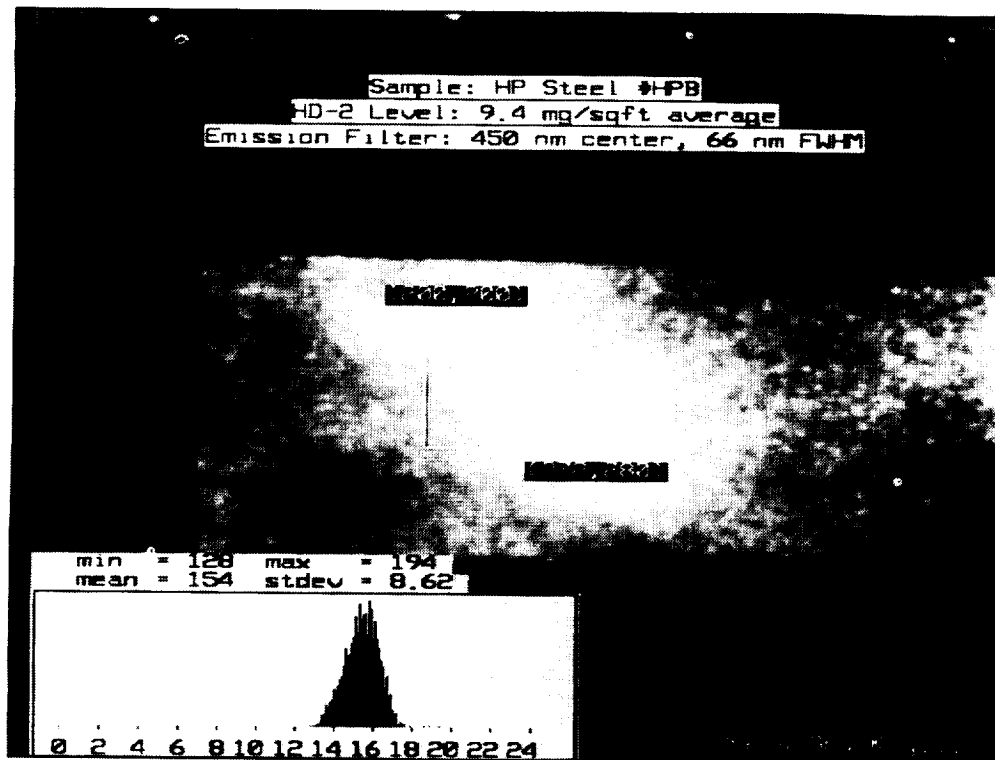


Figure 6. UVF Image of Grit Blasted HP-9 Steel Sample #HPB with 9.4 mg/ft² Average Level of Applied HD-2 Grease. Emission Filter - 450 nm CWL, 66 nm FWHM

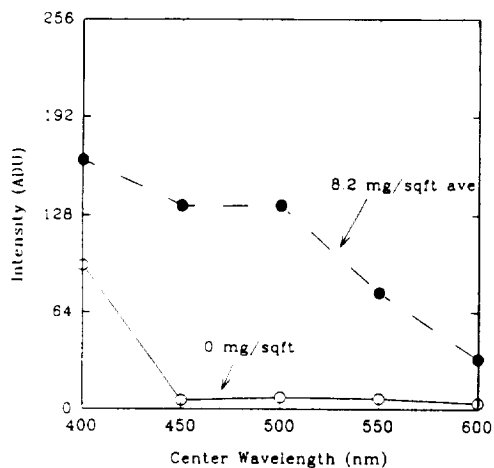


Figure 7. Measured Intensity as a Function Filter Center Wavelength, Sample: Grit Blasted 6061 T6 Aluminum, HD-2 Level: 0 and 8.2 mg/ft² Average

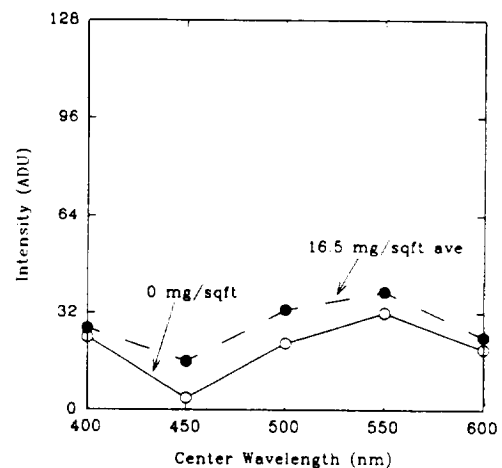


Figure 8. Measured Intensity as a Function Filter Center Wavelength, Sample: Carbon Phenolic Composite HD-2 Level: 0 and 16.5 mg/ft² Average

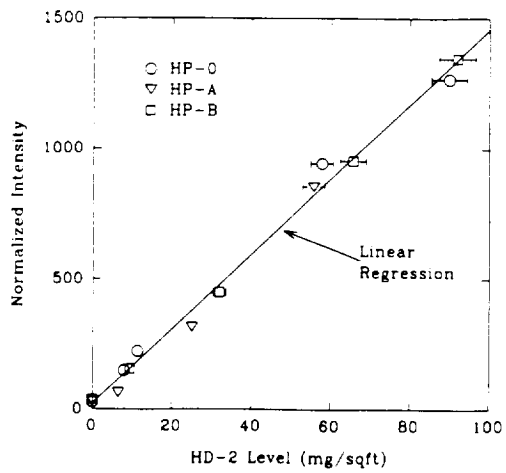


Figure 9. Normalized Intensity as a Function of Applied HD-2 Level for Samples HPO, HPA and HPB. Emission Filter = 450 nm CWL, 28 nm FWHM

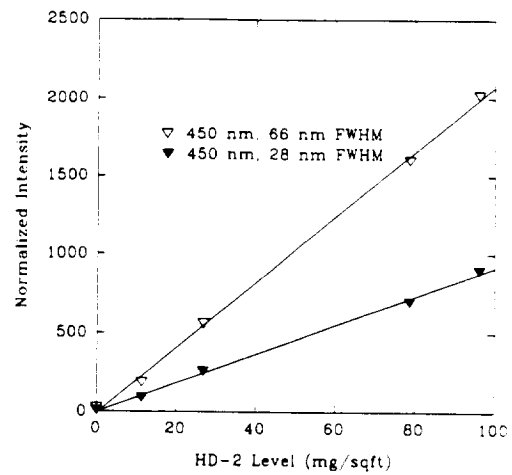


Figure 10. Normalized Intensity as a Function of Applied HD-2 Level, for 6061 T6 Aluminum.

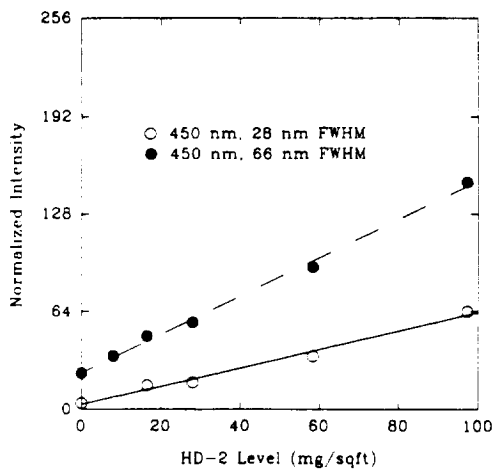


Figure 11. Normalized Intensity as a Function of HD-2 Level for Cermatel 1207/1208 Coating Sample.

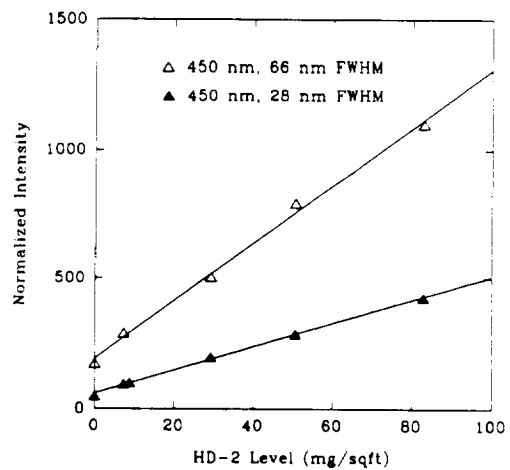


Figure 12. Normalized Intensity as a Function of HD-2 Level for Carbon Phenolic Composite Sample

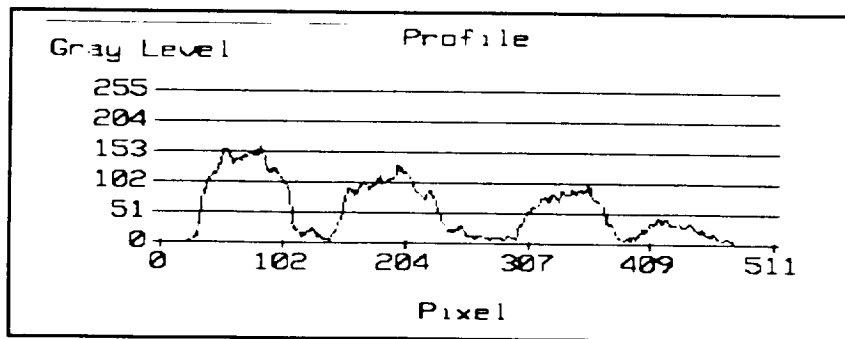


Figure 13. Profiles Through Regions of Contamination for 2.12 sec Integration Time, Nominal HD-2 Levels of 84, 63, 42, and 21 $\mu\text{g}/\text{cm}^2$ on Liner.

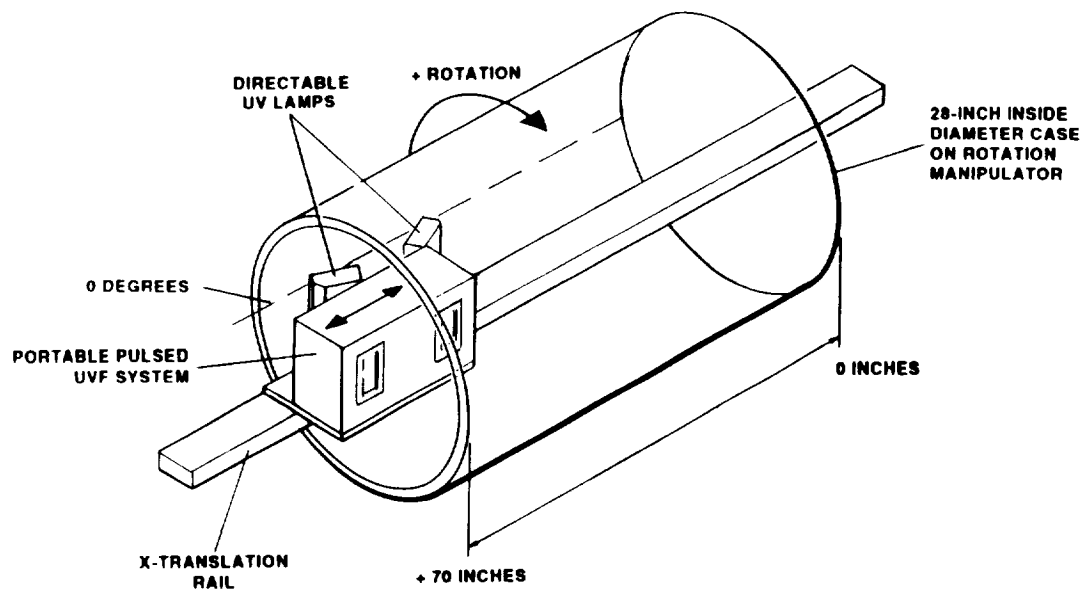


Figure 14. Inspection of 28-Inch ID Case with Portable UVF System.